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Regulation of the expression of the psychiatric risk gene *Cacna1c* during associative learning.

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Short title: Ca_v1.2 in hippocampal learning and memory

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Abstract

CACNA1C encodes the Ca_v1.2 L-type voltage gated calcium channel. Genetic variation in *CACNA1C* has been consistently identified as associated with risk for psychiatric disorders including schizophrenia, bipolar disorder, major depressive disorder and autism. Psychiatric risk loci are also enriched for genes involved in the regulation of synaptic plasticity. Here we show that the expression of *Cacna1c* is regulated in the rat hippocampus after context exposure, contextual fear conditioning and fear memory retrieval in a manner that correlates to specific memory processes. Using quantitative in situ hybridisation the expression was down-regulated in CA1 by brief exposure to a novel context and to a conditioned context, and up-regulated in the dentate gyrus after contextual fear conditioning. No changes were measured after prolonged context exposure followed by conditioning, a procedure that retards fear conditioning (latent inhibition), nor with fear memory recall leading to extinction. These results are consistent with a selective role for Ca_v1.2 in the consolidation of context memory and contextual fear memory, and with processes associated with the maintenance of the fear memory after recall. The dysregulation of *CACNA1C* may thus be related to associative memory dysfunction in schizophrenia and other psychiatric disorders.

Introduction

Long-term potentiation and the synaptic plasticity underlying long-term memory formation require *de novo* gene transcription and protein synthesis[1][2][3][4][5]. Previous research has shown changes in the expression of specific genes accompanying different aspects of associative learning; identifying separable molecular signatures of distinct memory processes including consolidation, recall and extinction[6][7][8][9][10]. Notably both early and late phases of transcriptional regulation following the induction of plasticity have been recognised[11][12].

Calcium influx into the post-synaptic neuron plays a critical role in regulating the changes in gene expression which accompany synaptic plasticity [13]. This calcium signal acts via signalling cascades to regulate the activity of transcription factors such as CREB. There are multiple routes for calcium to enter the cell, including via N-methyl-D-aspartate receptors (NMDA-R), GluA2-lacking calcium permeable α -amino-3-hydroxy-5-methyl-4-isoxazolepropionic acid receptors (AMPA-R) and indirectly, metabotropic glutamate receptor (mGluR), and voltage gated calcium channels (VGCCs). The regulation of expression of subunits of NMDA-Rs and mGluRs has been investigated following long term potentiation (LTP) revealing increased NR2B and mGluR1c expression evident in a late phase from 24 hrs following the induction of LTP in dentate gyrus granule cells [14]. These results demonstrate key channels are themselves subject to activity-dependent regulation following the induction of plasticity, with a late phase profile of transcriptional regulation. However much less is known about the regulation of expression of VGCCs during learning and plasticity events.

L-Type VGCCs are known to play a central role in controlling activity-dependent synaptic plasticity[15–17]. $\text{Ca}_v1.2$ channels, the predominant form of L-Type VGCCs in the mammalian brain, are ideally situated somato-dendritically to link neuronal activation to calcium

signalling and the regulation of gene expression[15, 16]. The C-terminal tail of the α_{1c} subunit of $Ca_v1.2$ (encoded by *CACNA1C*) directly binds calmodulin, a high affinity calcium binding protein, that through its interaction with target molecules including calcium-calmodulin kinases is key to triggering the signalling cascades which transmit the calcium signal to the nucleus, contributing to the regulation of activity-dependent genes such as BDNF.

Notably L-Type VGCCs, in particular the *CACNA1C* gene, have been strongly associated with risk for psychiatric disorders. Genome-wide association studies have shown a highly significant association between genetic variation in *CACNA1C* and risk for both bipolar disorder and schizophrenia, and cross disorder studies have suggested that genetic variation in the *CACNA1C* gene contributes risk across a range of psychiatric disorders including major depressive disorder and autism[18][19][20] [21][22] [23]. These findings are consistent with the more general observation that psychiatric risk loci are enriched for genes involved in the regulation of synaptic plasticity, including VGCCs, components of the NMDA receptor complex and the interactors of the Fragile X Mental Retardation Protein FMRP [24]. However, it is not clear whether *CACNA1C* is itself regulated transcriptionally during learning, and if so whether the regulation of *CACNA1C* is associated with specific phases of learning and memory.

Here we sought to further investigate the involvement of L-Type VGCCs in plasticity by investigating the regulation of the expression of the *Cacna1c* gene (the rodent homologue of *CACNA1C*) during associative learning. To examine learning related changes in *Cacna1c* expression we focussed on contextual fear conditioning (CFC) and memory (CFM), a form of associative learning known to depend on protein synthesis in the hippocampus [11]. In addition, we investigated the transcriptional regulation of *Cacna1c* after the recall of CFC under conditions of recall that promote the maintenance of the CFM (“reconsolidation”) or

extinction, both of which are independent associative memory mechanisms that depend on hippocampal protein synthesis[25][26], and in latent inhibition (LI), an effect in which pre-exposure to neutral stimulus retards subsequent conditioning [27] that depends on L-Type VGCCs [28]. We here report the selective regulation of *Cacna1c* during specific phases of associative memory formation, results that are likely to be of relevance in understanding the contribution of genetic variation in this gene to risk for psychiatric disorders.

Methods

Animals

Sixty-four male Lister Hooded rats (250 – 300 g) were housed in pairs in conventional NKP RC2R cages within a holding room maintained at 21°C on a 12h reversed light/dark cycle (lights on 8:00pm) and with ad libitum access to food (Harlan 2014 global rodent diet) and water. Experiments were conducted in the dark period. Animals were sacrificed from their home cages using a rising concentration of CO₂ at specific time points following each behaviour of interest. All procedures were conducted in accordance with local Cardiff University Ethical Committee approval and the United Kingdom 1986 Animals (Scientific Procedures) Act (Project license PPLs 30/2236 and 30/2722).

Behavioural procedures

Contextual fear conditioning (CFC) took place in a rat conditioning box with a metal grid floor (Standard modular test chamber for rat, Med Associates Inc., Vermont, USA). For CFC, individual animals were placed into the novel conditioning chamber for 2 mins prior to receiving a 0.5 mA scrambled footshock for 2 secs. They remained in the chamber for an additional 1 min before being returned to home cages. A *Novelty* group was exposed to the context for 2 mins without receiving a footshock and were returned to home cages. Conditioned animals were sacrificed 2, 4, 8 and 24 hrs later. Naïve home cage litter mates were sacrificed at the same time. *Novelty* animals were sacrificed 4 hrs following exposure.

A separate group of animals were individually pre-exposed to the context for 8 hrs before receiving the footshock to induce latent inhibition (*LI*) to control for gene expression associated with the experience of the footshock in the absence of CFM formation [6]. A pre-exposure (*PreExp*) group was also used to assess altered gene expression by the prolonged exposure to the context, spending 8 hrs in the box without a subsequent footshock. Both of the latter groups were sacrificed 4 hrs following return to home cages. Thus, a 4 hrs post-training to sacrifice delay is represented in all experimental groups.

A further cohort underwent CFC to measure the regulation of *Cacna1c* expression after recall and extinction. Forty-eight hrs later animals were returned to the conditioning context for either 2 mins (*Recall (2 min)*) or 10 mins (*Extinction (10 min)*). The 2 min exposure induces a cellular mechanism typically associated with reconsolidation of the recalled fear memory and which is required for the maintenance of the memory, whereas the prolonged re-exposure leads to the formation of an inhibitory associative extinction memory characterised by reduced conditioned freezing behaviour [29]. The recall groups were sacrificed 2 hrs following re-exposure to the context along with the conditioned group that were not re exposed to the training context (*No Recall*). This time was selected because our own previous data suggest that altered gene expression can be measured at this delay after recall (e.g. Trent et al. 2015) and that molecular events associated with recall occur in a shorter temporal span than after learning (Alberini et al. 2005).

n = 6 for all groups except CFC groups sacrificed 2 and 8 hrs after conditioning (n = 4)

Behavioural analysis

Freezing behaviour served as a measure of unconditioned and conditioned fear to the context during the training and recall tests and was defined as complete immobility except for respiration. The behaviour was digitally recorded and quantified by two independent scorers blind to the experimental group. One unit of freezing behaviour was defined as a

continuous absence of movement sampled 1s in every 10s. The percentage of time spent freezing was calculated every 2 min, or 1 min immediately after the footshock (post-unconditioned stimulus (Post-US)). The data by the two scorers were concordant. The scores were expressed as mean \pm SEM. Repeated measures ANOVAs using Mauchley's test for sphericity with Greenhouse-Geisser correction were used to compare freezing levels before US (Pre-US) and post-US phases during conditioning and to analyse freezing levels in the Recall (2min) and Extinction (10min) groups during the subsequent recall test.

In situ hybridisation

As described previously [30], brains were removed immediately post-mortem, fresh frozen on dry-ice and stored at -80°C . Coronal sections ($14\text{ }\mu\text{m}$) through the dorsal hippocampus were made (Leica Microsystems CM1860UV), mounted on poly-L-lysine coated glass microscope slides and air-dried at RT. Sections were fixed in 4 % PFA solution and dehydrated before storage at 4°C in 95% ethanol until required.

For hybridisation, a cDNA antisense probe (45-mers, 3' - TCGAAGTAGGTGGAGTTGACCACG-TACCACACTTTGTACT GGTGC -5' complementary to nucleotides 3940-3896, NM_012517.2) were synthesized commercially (SigmaGenosys). The probe was 3'-end labelled with [α -thio ^{35}S] dATP (1200 Ci/mmol; Perkin Elmer-NEN) in a 30:1 molar ratio of radiolabeled ATP:oligonucleotide using terminal deoxynucleotidyl transferase (30U/ μL , Promega).

Specific activity of the ^{35}S -labelled probe was between 2.0×10^5 and 3.0×10^5 dpm/ μL probe. To define non-specific hybridization, adjacent slide-mounted sections were incubated with radiolabeled oligonucleotide in the presence of an excess (80X) concentration of unlabelled oligonucleotide probe. After hybridization, sections and a ^{14}C ladder (American Radiolabelled Chemicals, Saint Louis, USA) for quantification, were exposed to Kodak BioMax MR X-ray film (Sigma-Aldrich Company Ltd) for 7 days before the autoradiograms were developed.

In situ hybridisation semi-quantitative analysis

Films were analysed using ImageJ software (<http://rsbweb.nih.gov/ij/>). Optical density values were converted to concentrations using a standard curve calculated by reference to the ^{14}C ladder. Measurements were taken from each region of interest including corresponding regions that defined the non-specific hybridisation signal. A specific signal was then calculated for each region of interest by subtracting the mean total and non-specific values for an individual rat. The mean concentration in each region for each animal was then divided by the region mean in the respective control group to give a standardized grain count (percent) for each group. Results were expressed as mean \pm SEM. Standardized results were analysed by ANOVA. Dunnett's test was used for comparisons to the control Naïve group, and Bonferroni tests for other comparisons were conducted where ANOVAs were significant. Pearson correlation analysis was performed to investigate the association between freezing behaviour and *Cacna1c* expression.

Results

CFC rats exhibited an increase in freezing behaviour after footshock

Freezing behaviour was scored for all animals that were exposed to the training context. There were no differences in freezing behaviour during the first 2 mins exposure to the context between groups ($F(3,20)_{\varepsilon=1} = 1.990$, $p = 0.148$, Fig. 1.). In those animals that received a footshock (CFC and LI groups), there was a significant interaction between freezing behaviour during Pre-US and Post US-training phases and group ($F(1,10)_{\varepsilon=1} = 34.747$, $P < 0.000$). During the Post-US phase, rats in the CFC group exhibited greater freezing following the footshock compared to LI animals that experienced prolonged pre-exposure to the context ($F(1,10)_{\varepsilon=1} = 25.879$, $P < 0.001$). Thus the CFC but not LI group showed successful acquisition of CFM [31].

Basal expression of Cacna1c

ISH was conducted to determine the basal expression profile of *Cacna1c*. Basal levels of expression were compared between the prefrontal cortex (PFC), cerebellum and hippocampus (Fig. 2.). Expression of *Cacna1c* was highest in the dentate gyrus (dg) and CA3 sub-regions of the hippocampus. Relatively high levels were also seen in the granule layer of the cerebellum. While much lower, expression in the PFC was highest in the medial PFC.

Regulated expression of Cacna1c in CA1 by exposure to a novel context and in dg after CFC

There was a reduction in *Cacna1c* expression in the CA1 in the Novelty group compared to naïve controls ($t(10) = 2.933$, $P = 0.015$, though this did not survive Dunnett's correction for multiple comparisons across all control groups ($P = 0.120$)(Fig. 3.). This reduction was measured 4 hrs after novel context exposure. No differences were observed in the CA3 or dg ($F(3,23) = 1.331$, $P = 0.292$ and $F(3,23) = 1.229$, $P = 0.325$, respectively) in the *Novelty*, *PreExp* or *LI* groups.

Expression of *Cacna1c* increased following CFC specifically in the dg ($F(4,21) = 2.823$, $P = 0.048$) when compared with naïve controls. *Post-hoc* Bonferroni tests revealed a significant difference between expression at 2 hrs and 24 hrs post conditioning, with increased expression of *Cacna1c* at 24 hrs ($P = 0.046$).

There was no effect of CFC at any time point on expression in the CA1 or CA3 regions of the hippocampus ($F(4,21) = 0.149$, $P = 0.961$ and $F(4,21) = 0.666$, $P = 0.622$, respectively).

An association between freezing behaviour and gene expression selectively in the dg is further highlighted since responses during training (post-US or novel context exposure) was correlated with the expression of *Cacna1c* 4 hours later in the dg ($r(12) = 0.540$, $P = 0.046$), but not in CA3 ($r(12) = 0.191$, $P = 0.506$) or CA1 ($r(12) = 0.253$, $P = 0.384$).

Prolonged exposure to the conditioned context results in reduced freezing behaviour

All animals successfully acquired CFM as observed by increased freezing following the footshock compared to the 2 mins before the US during conditioning ($F(1,15)_{\epsilon=1} = 293.515$, $p = 0.000$; Group X Freezing Behaviour $F(2,15)_{\epsilon=1} = 1.238$, $p = 0.318$), Fig. 4.). Forty-eight hours after CFC, animals re-exposed to the training context exhibited high levels of freezing indicative of successful recall of CFM. There were no Group X Freezing Behaviour differences between Post-US phase and the first 2 mins of recall ($F(1,10)_{\epsilon=1} = 0.237$, $p = 0.637$). Prolonged 10 min exposure to the context resulted in reduced levels of conditioned freezing indicative of the extinction of CFM ($F(2.296, 11.479)_{\epsilon=0.574} = 14.531$, $p = 0.001$). Freezing levels were significantly reduced in the last 2 mins of the session compared to the first 2 min after recall ($F(1, 5)_{\epsilon=1} = 93.889$, $p = 0.000$).

Reduced expression of *Cacna1c* in the CA1 following brief recall

Cacna1c expression differed in the CA1 region between the Recall (2 min) and Recall (10 min) extinction groups 2 hr after recall of CFM ($F(2,15) = 4.628$, $p = 0.027$, Fig. 5.). Post-hoc Bonferroni tests revealed a significantly reduced expression in animals that underwent the short 2 min recall session compared to those that experienced the 10 min extinction session ($p = 0.029$). There were no differences in expression of *Cacna1c* in the CA3 or dg region of the hippocampus in any of the three groups ($F(2,15) = 0.358$, $P = 0.705$ and ($F(2,15) = 0.196$, $P = 0.824$, respectively). There was weak negative correlation between freezing behaviour in the last 2 min of the recall test and *Cacna1c* expression in CA1 ($r(10) = 0.504$, $P = 0.094$), but not in CA3 ($r(10) = 0.027$, $P = 0.933$) or dg ($r(10) = 0.088$, $P = 0.785$).

Discussion

We show that the expression of *Cacna1c* was regulated in the hippocampus in an activity-dependent manner and specifically with distinct learning and memory events. Basal expression of *Cacna1c* was found to be highest in the dg region of the hippocampus, followed by the CA3, and much lower levels measured in CA1. *In situ* hybridisation revealed that exposure to a novel context down regulated *Cacna1c* expression in the CA1. Increased expression was seen in the dg 24 hrs following CFC. Decreased expression in the hippocampal CA1 field also followed re-exposure to the conditioned context. However, the retrieval-associated decrease was seen in rats exposed for 2 min but not a 10 min context exposure, which is associated with the extinction of CFM, indicating that retrieval associated regulation of *Cacna1c* expression is not related to extinction processes.

Delayed regulated expression of Cacna1c in the dg following CFC

There was an increased expression of *Cacna1c* 24 hrs compared to levels 2 hrs following CFC. There were no changes observed in other regions of the hippocampus, or at other time points investigated. This indicates that the expression of *Cacna1c* is related to the consolidation of CFM, selectively in the dg.

This increase in expression 24 hrs following CFC suggests a role for $Ca_v1.2$ channels in a long-lasting alteration in the synapse as a result of plasticity. Previous studies have found delayed upregulation of gene expression in subunits of glutamate receptors in the dg following the induction of LTP in hippocampus [14, 32]. Thomas et al., (1996)[14] found an increase in the GluR2B subunit of NMDA receptors evident from 24 hrs, peaking at 48 hrs, along with increases in mGluR1c which only became evident at 96 hrs following induction of LTP. It was proposed that these late-phase profiles of expression may relate to cascades of events that are required for the maintenance of LTP. Persistence of long-term memory has also been found to be related to delayed protein synthesis of BDNF at around 12 hrs following CFC

[33]. The increase of expression in *Cacna1c* observed here may indicate a delayed role in consolidation and long-term maintenance of CFM. Increases in *Cacna1c* expression in the dg with CFC are consistent with a role for this hippocampal region in CFM acquisition[34][35]. As the changes were specifically seen in the dg, it is also possible that this increase in *Cacna1c* in relation to learning could contribute to the recently reported role of $\alpha 1c$ subunit-containing $Ca_v1.2$ channels in regulating neurogenesis in the dg[36][37].

Selective reduced expression of Cacna1c in CA1 following context exposure

We show that both unconditioned and conditioned context exposure leads to a decrease in *Cacna1c* expression in the CA1. This regulation in CA1 may not be directly linked to novelty processing *per se*, a function co-ordinated by the dg and CA3 regions [38][39], but with the role of the hippocampus in the formation and storage of the conjunctive representation of the context necessary for the consolidation and reconsolidation of CFC[40][41][42]. The regulation of *Cacna1c* expression in CA1 is therefore consistent with its role as a key region for the consolidation and reconsolidation of contextual fear (CS-US) memory[43][44][45]. The regulation of *Cacna1c* expression in both dg and CA1 after acquisition but not recall (CA1 only) is consistent with the differential contributions of these two hippocampal regions to CFM acquisition and retrieval [46].

We also noted that the regulation in *Cacna1c* expression was sensitive to the duration of context exposure with reductions in mRNA levels seen after short exposures (*Novelty and Recall (2 min) groups*), but not longer periods (*PreExp and Recall (10 min) groups*). This observation may relate to a selective role for $Ca_v1.2$ in context memory processing during consolidation & reconsolidation rather than pavlovian CS-US and CS-no US events related to CFM encoding, LI and extinction.

In summary, the regulation of *Cacna1c* transcription in the hippocampus after conditioned or unconditioned context exposure and following CFC indicate a role for $Ca_v1.2$ in specific

memory processes; down-regulation of expression correlated with CA1-associated contextual memory and upregulation of expression in the dg associated with CFM encoding. To determine a causal role for Ca_v1.2, in these distinct memory processes by region requires more refined genetic or molecular rodent models.

Implications for the role of Ca_v1.2 in hippocampal-dependent learning and memory

There has been long standing pharmacological evidence for the role of LVCCs in the consolidation and extinction of fear memory[28][25]. Genetic models have indicated that there may be differential contribution of the major brain isoforms Ca_v1.2 and Ca_v1.3 (encoded by the *CACNA1D* gene linked to risk for bipolar disorder[47] to different components of associative memory. Mice with forebrain knock out of *Cacna1c* show no deficits in consolidation and extinction of CFC[48] and the consolidation of cued fear memory[49], while *Cacna1d* null mutants show impaired consolidation, but not extinction [50]. These data may indicate a specific role for Ca_v1.3 with fear memory formation. However, these models show compensatory adaptations in activity-dependent neuronal signalling[49][51], which make these data difficult to interpret. The role of Ca_v1.2 with associative memory processing is indicated in a gain-of-function model that shows enhanced cued and contextual fear memory via altered consolidation, strengthening and/or extinction[52]. The causal role of Ca_v1.2, selectively, in fear memory and behaviour remains to be determined using better genetic or molecular animal models.

Implications for psychiatric disorders

The *CACNA1C* gene has been strongly associated with risk for psychiatric disorders including schizophrenia and bipolar disorder in genome-wide association studies [23][21][22][19][20]. These disorders are known to be associated with cognitive alterations that include alterations in learning, memory and affective processing. The current results show that *Cacna1c* expression is regulated in distinct regions of the hippocampus at the transcriptional

level and which correlate with context processing required for specific components of associative CFM formation and maintenance. Genetic variation in *Cacna1c* may impact on the plasticity during key phases of associative learning. It is likely that any distinction in the role of *Cacna1c* in these aspects of learning will be further revealed by investigating the functional regulation of calcium influx through LVGCCs. Our results thus provide additional evidence that a link exists between $\text{Ca}_v1.2$ and distinct behavioural domains associated with common behavioural phenotypic features of psychiatric disorders including schizophrenia, ASD and BD.

Fig. 1. Freezing behaviour (% time spent freezing) during Pre-US and Post-US phases of CFC. Freezing behaviour in the fear conditioned *CFC* group was greater than in the *LI* group that underwent prolonged pre-exposure to the context before footshock. Bars represent average freezing behaviour for each group. Rats in the *Novelty* and *PreExp* groups were exposed to the context for 3 min and 8 hours respectively and did not receive a footshock. $n = 6$ for all groups. *** $P < 0.001$.

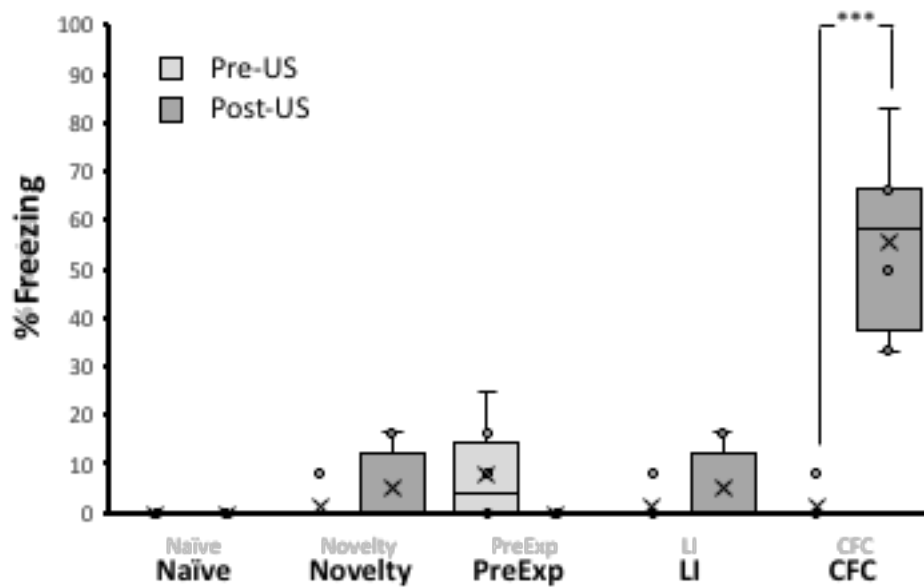


Fig. 2. Basal expression of *Cacna1c* mRNA. **a** Quantification of relative *in situ* hybridisation (ISH) density values. Specific hybridization was calculated by subtracting the “non-specific” signal, defined by excess unlabelled oligonucleotide probe, from “total” values normalised to the specific signal measured in the medial PFC (mPFC). Greatest expression was observed in the dentate gyrus (dg). Bars represent mean of the specific hybridisation values. Error bars are +/- SEM. n = 4. **b** Representative ISH autoradiogram images of *Cacna1c* expression in the PFC, cerebellar and hippocampal subregions. Total hybridization of the probe is shown on the left-hand side and non-specific hybridization on the right.

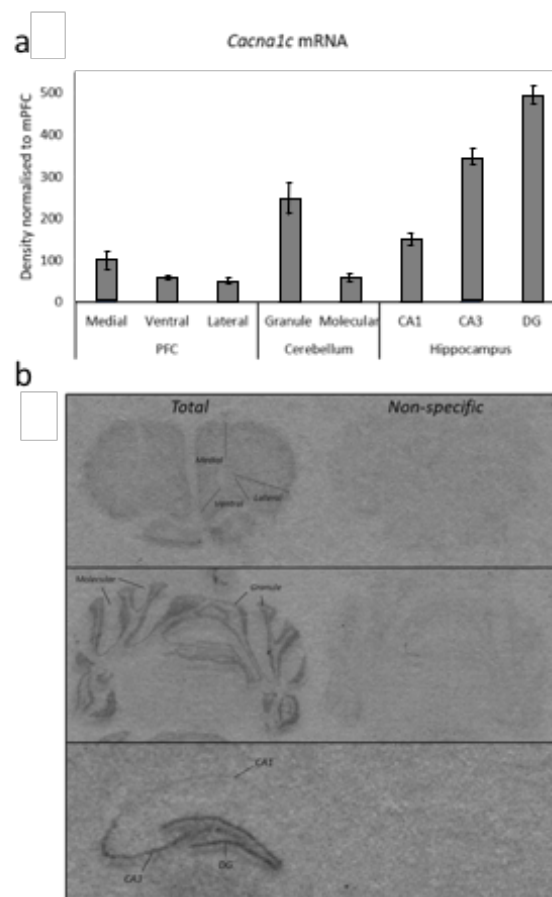


Fig. 1. Expression of *Cacna1c* in CA1, CA3 and dg sub-regions of the hippocampus following different learning events. **a** Representative ISH autoradiogram images of *Cacna1c* expression in a *Naïve* (left) and novel context (*Novelty*) exposed (right) rat. **b** A reduction in expression was measured in CA1 following exposure to novel context compared to naïve animals. Expression in the dg following CFC showed an increase at 24 hrs compared to levels at 2 hrs. Bars represent mean specific hybridisation values normalised to Naïve control. Error bars are +/- SEM. n = 6 for all groups except 2 and 8 hrs (n = 4). * P < 0.05.

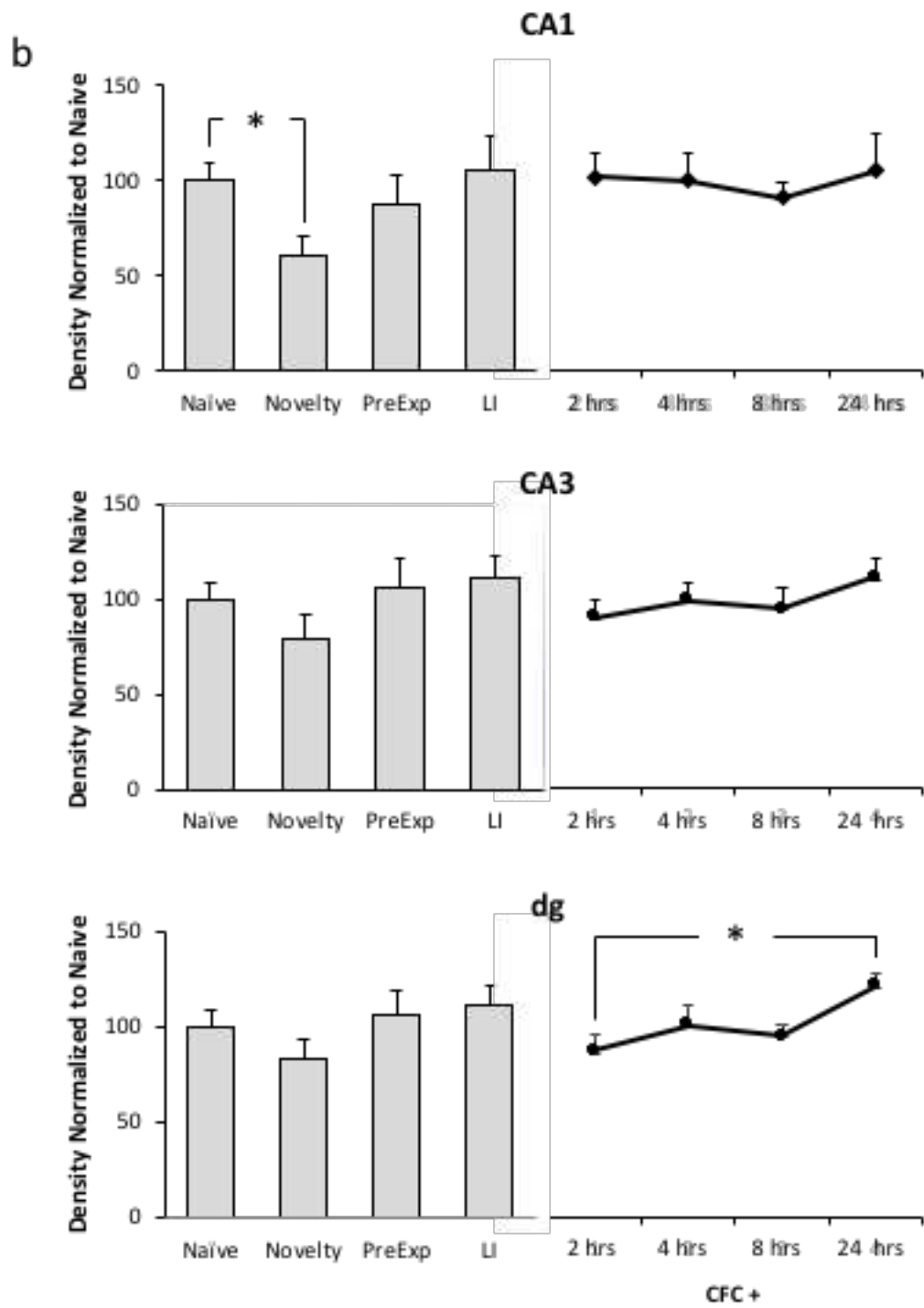
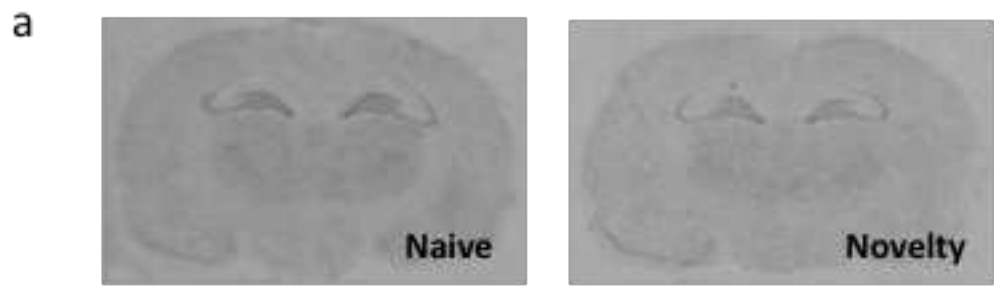


Fig. 2. Freezing behaviour during CFC and recall. There was an increase in freezing following US presentation in all groups ($t(17) = -16.898$, $P < 0.001$) indicating acquisition of CFM. The reduction in conditioned freezing following prolonged 10 min re-exposure indicates acquisition of extinction in the Extinction group. Data points represent the average time spent freezing (%) for each group during each training and testing epoch. *** $P < 0.001$ $n = 6$ for all groups.

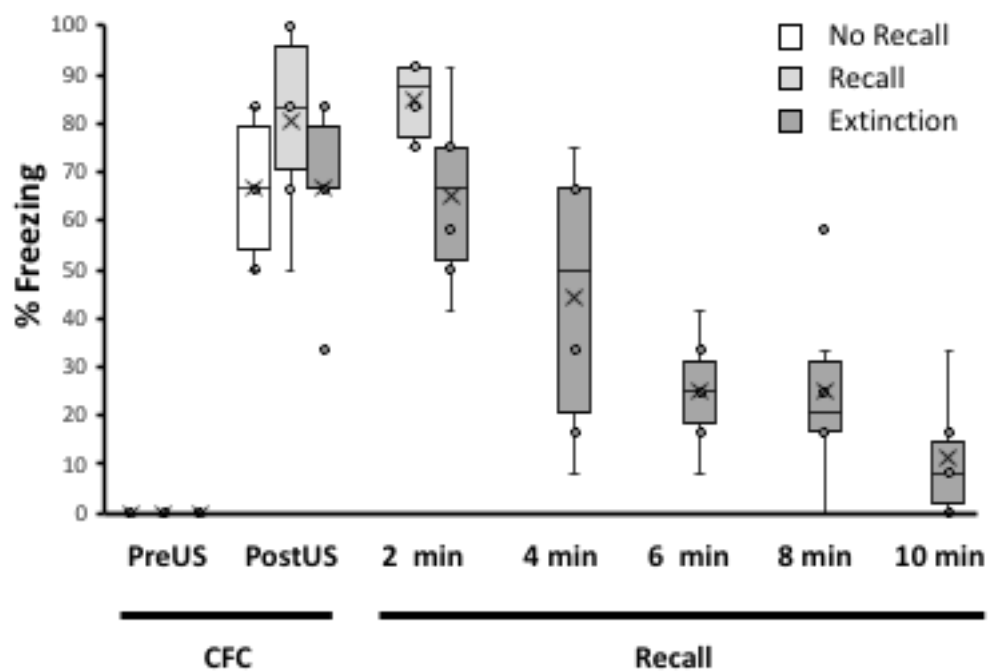
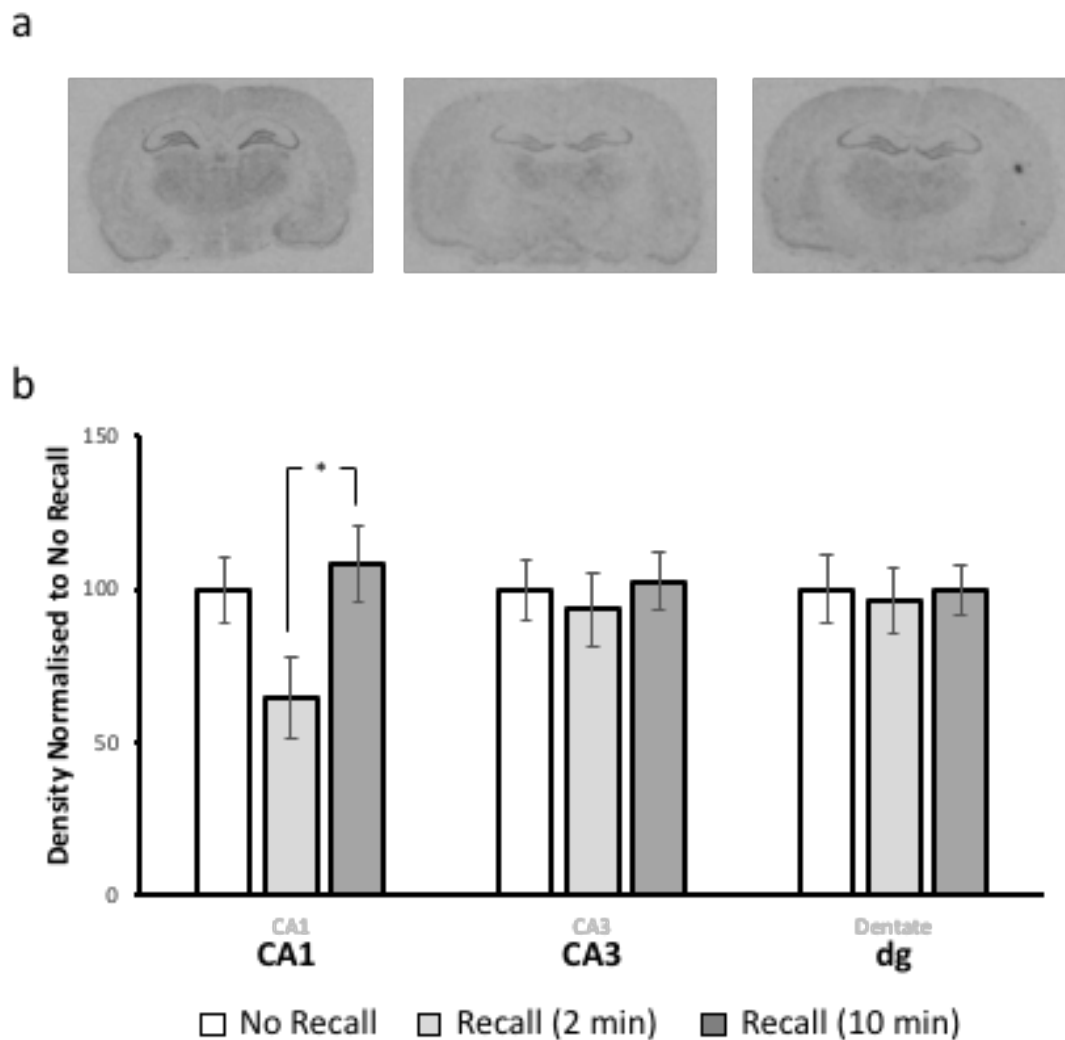


Fig. 3. Expression of *Cacna1c* 2 hrs following Recall (2 min) or Recall (10 min) session normalised to animals that underwent CFC alone (*No Recall group*). **a** Representative ISH autoradiograms of *Cacna1c* expression in a *No recall* (left), *Recall (2 min)* (middle) and *Recall (10 min)* (*Novelty*) exposed (right) rat. **b** There was a reduction in expression in the CA1 in the Recall (2 min) compared to the Recall (10 min) groups (* $P < 0.05$ Bonferroni corrected). Error bars are \pm SEM. * $P < 0.05$. $n = 6$ for all groups.



References

1. Davis HP, Squire LR (1984) Protein synthesis and memory: A review. *Psychol Bull* 96:518–559 . doi: 10.1037/0033-2909.96.3.518
2. Stanton P, Sarvey J (1984) Blockade of long-term potentiation in rat hippocampal CA1 region by inhibitors of protein synthesis. *J Neurosci* 4:3080–3088
3. Krug M, Lössner B, Ott T (1984) Anisomycin blocks the late phase of long-term potentiation in the dentate gyrus of freely moving rats. *Brain Res Bull* 13:39–42 . doi: 10.1016/0361-9230(84)90005-4
4. Nguyen P V, Abel T, Kandel ER (1994) Requirement of a Critical Period of Transcription for Induction of a Late Phase of LTP. *Science* 265:1104–1107
5. Bourtchuladze R, Frenguelli B, Blendy J, et al (1994) Deficient long-term memory in mice with a targeted mutation of the cAMP-responsive element-binding protein. *Cell* 79:59–68 . doi: 10.1016/0092-8674(94)90400-6
6. Hall J, Thomas KL, Everitt BJ (2000) Rapid and selective induction of BDNF expression in the hippocampus during contextual learning. *Nat Neurosci* 3:533–535 . doi: 10.1038/75698
7. Lee JLC (2004) Independent Cellular Processes for Hippocampal Memory Consolidation and Reconsolidation. *Science* (80-) 304:839–843 . doi: 10.1126/science.1095760
8. Scholz B, Doidge AN, Barnes P, et al (2016) The regulation of cytokine networks in hippocampal CA1 differentiates extinction from those required for the maintenance of contextual fear memory after recall. *PLoS One* 11:1–29 . doi:

10.1371/journal.pone.0153102

9. Barnes P, Kirtley A, Thomas KL, Group C-D (2012) Quantitatively and qualitatively different cellular processes are engaged in CA1 during the consolidation and reconsolidation of contextual fear memory. *Hippocampus* 381:1371–1379 . doi: 10.1016/S0140-6736(12)62129-1
10. Quirk GJ, Mueller D (2008) Neural mechanisms of extinction learning and retrieval. *Neuropsychopharmacology* 33:56–72 . doi: 10.1038/sj.npp.1301555
11. Bourtchouladze R, Abel T, Berman N, et al (1998) Different Training Procedures Recruit Either One or Two Critical Periods for Contextual Memory Consolidation, Each of Which Requires Protein Synthesis and PKA. *Learn Mem* 5:365–374 . doi: 10.1101/lm.5.4.365
12. Igaz LM, Vianna MRM, Medina JH, Izquierdo I (2002) Two time periods of hippocampal mRNA synthesis are required for memory consolidation of fear-motivated learning. *J Neurosci* 22:6781–9 . doi: 20026642
13. Sheng M, Thompson M, Greenberg M (1991) CREB: a Ca(2+)-regulated transcription factor phosphorylated by calmodulin-dependent kinases. *Science* (80-) 252:1427–30
14. Thomas KL, Davis S, Hunt SP, et al (1996) Alterations in the Expression of Specific Glutamate Receptor Subunits Following Hippocampal LXP in Vivo. 197–208
15. Berger SM, Bartsch D (2014) The role of L-type voltage-gated calcium channels Cav1.2 and Cav1.3 in normal and pathological brain function. *Cell Tissue Res* 357:463–476 . doi: 10.1007/s00441-014-1936-3
16. Bengtson CP, Bading H (2012) Nuclear Calcium Signaling. In: *Advances in experimental medicine and biology*. pp 377–405

17. Kabir ZD, Martínez-Rivera A, Rajadhyaksha AM (2017) From Gene to Behavior: L-Type Calcium Channel Mechanisms Underlying Neuropsychiatric Symptoms. *Neurotherapeutics*. doi: 10.1007/s13311-017-0532-0
18. Purcell SM, Moran JL, Fromer M, et al (2014) A polygenic burden of rare disruptive mutations in schizophrenia. *Nature* 506:185–190 . doi: 10.1038/nature12975
19. Jiang YH, Yuen RKC, Jin X, et al (2013) Detection of clinically relevant genetic variants in autism spectrum disorder by whole-genome sequencing. *Am J Hum Genet* 93:249–263 . doi: 10.1016/j.ajhg.2013.06.012
20. Splawski I, Timothy KW, Sharpe LM, et al (2004) CaV1.2 calcium channel dysfunction causes a multisystem disorder including arrhythmia and autism. *Cell* 119:19–31 . doi: 10.1016/j.cell.2004.09.011
21. Ripke S, O’Dushlaine C, Chambert K, et al (2013) Genome-wide association analysis identifies 13 new risk loci for schizophrenia. *Nat Genet* 45:1150–1159 . doi: 10.1038/ng.2742
22. De Rubeis S, He X, Goldberg AP, et al (2014) Synaptic, transcriptional and chromatin genes disrupted in autism. *Nature* 515:209–215 . doi: 10.1038/nature13772
23. Ripke S, Neale BM, Corvin A, et al (2014) Biological insights from 108 schizophrenia-associated genetic loci. *Nature* 511:421–427 . doi: 10.1038/nature13595
24. Hall J, Trent S, Thomas KL, et al (2015) Genetic risk for schizophrenia: Convergence on synaptic pathways involved in plasticity. *Biol Psychiatry* 77:52–58 . doi: 10.1016/j.biopsych.2014.07.011
25. Suzuki A (2004) Memory Reconsolidation and Extinction Have Distinct Temporal and Biochemical Signatures. *J Neurosci* 24:4787–4795 . doi: 10.1523/JNEUROSCI.5491-03.2004

26. Lee JLC, Everitt BJ, Thomas KL (2004) Independent cellular processes for hippocampal memory consolidation and reconsolidation. *Science* 304:839–843 . doi: 10.1126/science.1095760
27. Hall G, Rodriguez G (2010) Associative and nonassociative processes in latent inhibition: An elaboration of the Pearce–Hall model. In: Lubow RE, Weiner I (eds) *Latent inhibition: Data, theories, and applications to schizophrenia*. Cambridge University Press, Cambridge, pp 114–136
28. Bauer EP, Schafe GE, LeDoux JE (2002) NMDA receptors and L-type voltage-gated calcium channels contribute to long-term potentiation and different components of fear memory formation in the lateral amygdala. *J Neurosci* 22:5239–5249 . doi: 10.1523/JNEUROSCI.22/12/5239 [pii]
29. Trent S, Barnes P, Hall J, Thomas KL (2015) Rescue of long-term memory after reconsolidation blockade. *Nat Commun* 6:1–7 . doi: 10.1038/ncomms8897
30. Hall J, Thomas KL, Everitt BJ (2000) Rapid and selective induction of BDNF expression in the hippocampus during contextual learning. *Nat Neurosci* 3:533–535 . doi: 10.1038/75698
31. Kiernan MJ, Westbrook RF (1993) Effects of Exposure to a To-Be-Shocked Environment upon the Rat's Freezing Response: Evidence for Facilitation, Latent Inhibition, and Perceptual Learning. *Q J Exp Psychol Sect B* 46:271–288 . doi: 10.1080/14640749308401089
32. Thomas K, Davis S, Laroche S, Hunt S (1994) Regulation of the expression of NR1 NMDA glutamate receptor subunits during hippocampal LTP. *Neuroreport* 6:119–123
33. Bekinschtein P, Cammarota M, Izag LM, et al (2007) Persistence of Long-Term Memory Storage Requires a Late Protein Synthesis- and BDNF- Dependent Phase in

- the Hippocampus. *Neuron* 53:261–277 . doi: 10.1016/j.neuron.2006.11.025
34. Lee I, Kesner RP (2004) Encoding versus retrieval of spatial memory: Double dissociation between the dentate gyrus and the perforant path inputs into CA3 in the dorsal hippocampus. *Hippocampus* 14:66–76 . doi: 10.1002/hipo.10167
 35. Hernández-Rabaza V, Hontecillas-Prieto L, Velázquez-Sánchez C, et al (2008) The hippocampal dentate gyrus is essential for generating contextual memories of fear and drug-induced reward. *Neurobiol Learn Mem* 90:553–559 . doi: 10.1016/j.nlm.2008.06.008
 36. Lee AS, De Jesus-Cortes H, Kabir ZD, et al (2016) The neuropsychiatric disease-associated gene *cacna1c* mediates survival of young hippocampal neurons. *eNeuro* 3:ENEURO.0006-16.2016 . doi: 10.1523/ENEURO.0006-16.2016
 37. Temme SJ, Bell RZ, Fisher GL, Murphy GG (2016) Deletion of the Mouse Homolog of CACNA1C Disrupts Discrete Forms of Hippocampal- Dependent Memory and Neurogenesis within the Dentate Gyrus. *eNeuro* 3:e0118-16. 1–14 . doi: 10.1523/ENEURO.0118-16.2016
 38. Kesner RP, Rolls ET (2015) A computational theory of hippocampal function, and tests of the theory: New developments. *Neurosci Biobehav Rev* 48:92–147 . doi: 10.1016/j.neubiorev.2014.11.009
 39. Hunsaker MR, Rosenberg JS, Kesner RP (2008) The role of the dentate gyrus, CA3a,b, and CA3c for detecting spatial and environmental novelty. *Hippocampus* 18:1064–1073 . doi: 10.1002/hipo.20464
 40. Matus-Amat P (2004) The Role of the Dorsal Hippocampus in the Acquisition and Retrieval of Context Memory Representations. *J Neurosci* 24:2431–2439 . doi: 10.1523/JNEUROSCI.1598-03.2004

41. Matus-Amat P, Higgins EA, Sprunger D, et al (2007) The Role of Dorsal Hippocampus and Basolateral Amygdala NMDA Receptors in the Acquisition and Retrieval of Context and Contextual Fear Memories. *Behav Neurosci* 121:721–731 . doi: 10.1037/0735-7044.121.4.721
42. Chang SD, Chen DY, Liang KC (2008) Infusion of lidocaine into the dorsal hippocampus before or after the shock training phase impaired conditioned freezing in a two-phase training task of contextual fear conditioning. *Neurobiol Learn Mem* 89:95–105 . doi: 10.1016/j.nlm.2007.07.012
43. Shimizu E, Tang Y-P, Rampon C, Tsien JZ (2000) NMDA Receptor: Dependent Synaptic Reinforcement as a Crucial Process for Memory Consolidation. *Science* (80-) 290:1170–1174 . doi: 10.1126/science.290.5494.1170
44. Dumas S (2005) Encoding, consolidation, and retrieval of contextual memory: Differential involvement of dorsal CA3 and CA1 hippocampal subregions. *Learn Mem* 12:375–382 . doi: 10.1101/lm.81905
45. Lux V, Maseck OA, Herlitze S, Sauvage MM (2017) Optogenetic Destabilization of the Memory Trace in CA1: Insights into Reconsolidation and Retrieval Processes. *Cereb Cortex* 27:841–851 . doi: 10.1093/cercor/bhv282
46. Kesner RP (2017) An analysis of dentate gyrus function (an update) An analysis of dentate gyrus function (an update). *Behav Brain Res* 0–1 . doi: 10.1016/j.bbr.2017.07.033
47. Ament SA, Szelinger S, Glusman G, et al (2015) Rare variants in neuronal excitability genes influence risk for bipolar disorder. *Proc Natl Acad Sci* 112:3576–3581 . doi: 10.1073/pnas.1424958112
48. McKinney BC, Sze W, White JA, Murphy GG (2008) L-type voltage-gated calcium

channels in conditioned fear: a genetic and pharmacological analysis. *Learn Mem* 15:326–34 . doi: 10.1101/lm.893808

49. Langwieser N, Christel CJ, Kleppisch T, et al (2010) Homeostatic Switch in Hebbian Plasticity and Fear Learning after Sustained Loss of Cav1.2 Calcium Channels. *J Neurosci* 30:8367–8375 . doi: 10.1523/JNEUROSCI.4164-08.2010
50. McKinney BC, Murphy GG (2006) The L-type voltage-gated calcium channel Cav1.3 mediates consolidation, but not extinction, of contextually conditioned fear in mice. *Learn Mem* 13:584–589 . doi: 10.1101/lm.279006
51. Poetschke C, Dragicevic E, Duda J, et al (2015) Compensatory T-type Ca^{2+} channel activity alters D2-autoreceptor responses of Substantia nigra dopamine neurons from Cav1.3 L-type Ca^{2+} channel KO mice. *Sci Rep* 5:1–16 . doi: 10.1038/srep13688
52. Bader PL, Faizi M, Kim LH, et al (2011) Mouse model of Timothy syndrome recapitulates triad of autistic traits. *Proc Natl Acad Sci* 108:15432–15437 . doi: 10.1073/pnas.1112667108

